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(54) **Method and device for detection of and protection against the effect of static magnatic fields on magnetoelastic force transducer.**

(57) Method and device for detection of and protection against the effect of disturbing static and/or quasi-static magnetic fields on measurement with a magnetoelastic force and torque transducer which transducer is magnetized by a symmetrical, periodic supply current, the Fourier representation of which only comprises a fundamental wave and odd harmonics of this fundamental wave. If the magnetic flux density B generated in a body of ferromagnetic material by a sinusoidal symmetrical magnetic field strength (magnetization) exhibits even harmonics, this means that the body also has superimposed static and/or quasi-static magnetization. According to the invention the content of even harmonics determined and measured, respectively. The content corresponds to the degree of static and/or quasi-static magnetization and is used as input signal to a regulator (11) which, with the aid of a direct current in, for example, a separate winding (14) reduces the static and/or quasi-static magnetization to zero.

EP 0 434 089 A1

METHOD AND DEVICE FOR DETECTION OF AND PROTECTION AGAINST THE EFFECT OF STATIC MAGNETIC FIELDS ON MAGNETOELASTIC FORCE TRANSDUCER

The invention relates to a method and device for detection of and protection against the effect of static and slowly varying magnetic fields on magnetoelastic force transducer according to the precharacterising part of claim 1.

Such force transducers are intended to measure mechanical stresses with the aid of the magnetoelastic effect.

The magnetoelastic effect is a phenomenon whereby the magnetic permeability of a ferromagnetic material is changed when it is subjected to mechanical stresses.

Utilizing the above-mentioned effect for measuring mechanical forces and torques is an idea that arose over fifty years ago. In recent years this idea has attracted an increasingly greater interest.

Above all, the new amorphous materials with their very powerful magnetostriction have contributed to this increase. Also the possibility of using this technique for measuring torques in a contactless and very simple manner has increased the demand for it.

In addition, transducers based on the magnetoelastic effect are characterized by very high resistance with respect to the external environment and by a high signal power and hence low sensitivity to disturbance.

The design of the above-mentioned transducers varies considerably, but, in principle, the following summary can be made.

A body of a ferromagnetic material is subjected to a periodically alternating magnetic field strength (magnetization) by supplying current to an excitation winding.

The most primitive concept then only measures the inductance of the excitation winding in order thereby to obtain a measure of magnetic permeability of the material and hence a measure of the mechanical stress applied on the body of ferromagnetic material.

More sophisticated devices make use of a secondary winding for sensing the time rate of change of the magnetic flux generated by the magnetization.

With the aid of a secondary winding, it is also possible to measure the generated flux in a direction transverse to the magnetization, and in a direction making an angle of 45° with the principal stress direction of the mechanical stresses in the loaded body. This is the case with transducers known in the market under the trade marks PRESSDUCTOR® and TORDUCTOR®.

Another frequently used measuring principle comprises measuring the generated magnetic flux in several regions or measuring zones which are subjected to different mechanical stresses, and then forming the difference between these fluxes.

The most common method is to use two measuring zones, one of which is loaded with tensile stress and the other with compressive stress in the direction of the magnetic field. This is described, for example, in the EP-A-0,089,916 and US-A-4,506,554.

Another method is to measure the difference between the fluxes which are generated in a loaded and an unloaded zone.

Irrespective of which method is used in order to measure the permeability change in the magnetoelastic material, the magnetic hysteresis loop of the magnetization curve $B = f(H)$, with H being the magnetic field strength and B the magnetic flux density, which hysteresis loop is completed in each point in the material during a period of the magnetization, will be changed when the material is magnetized by a static magnetic field. This, of course, influences the measurement of the generated fluxes and leads to changes both of the measuring signal in an unloaded transducer, i.e. the zero signal, and of the sensitivity of the transducer to load.

If the transducer is magnetized by a static magnetic field to such an extent that the ferromagnetic material approaches saturation,the differential permeability and also the sensitivity of the transducer will be very low. However, the influence remains in connection with considerably lower fields.

To reduce the influence of this disturbance, attempts have been made to screen off external magnetic fields. However, screening off static or slowly varying, i.e. quasi-static, magnetic fields has proved to be a difficult technical problem. This problem may be particularly difficult when attempts are made to screen off external magnetic fields from shafts in connection with the measurement of torques.

The problem with static external magnetization may become particularly serious since static magnetization, by remanence in the transducer material, may give rise to permanent changes in the function of the transducer.

In general terms, as is well known, an arbitrary periodic signal may be represented as a Fourier series, i.e. a sum of sinusoidal signals or waves with different phases but with frequencies which are integral multiples of the frequency of the periodic signal. The wave with the lowest frequency, i.e. the frequency of the periodic signal, is called

the fundamental wave or fundamental tone and its frequency the fundamental frequency. The others waves with frequencies which are higher integral multiples of this fundamental frequency are called harmonic waves or just harmonics. Depending on whether the frequency of a harmonic is two times, three times or several times the fundamental frequency, reference is made to the second harmonic wave or tone, the third harmonic wave or tone, etc., of the periodic signal.

The invention utilizes the fact that the B-H curve, in case of normal magnetization without static fields, is completely symmetrical with respect to the origin of B-K coordinate system.

One way of expressing the above in mathematical terms is that the magnetic flux density B changes signs after half a period, i.e.

$$B(t+T/2) = -B(t)$$

where

B = the magnetic flux density,
t = the time,
T = the period of the magnetization.

If the magnetic field strength H is purely sinusoidal, the above symmetry means that the Fourier representation of the magnetic flux density generated in saturated ferromagnetic material as a function of the time will only comprise a fundamental wave and odd-numbered harmonics.

A material with a completely linear B-H curve gives no harmonics at all, whereas a saturated material, with a non-linear B-H curve exhibits a very high content of harmonics, above all of the third harmonic but also of harmonics of higher order.

When a material has a static magnetization superimposed on the sinusoidal, symmetrical magnetization, however, the symmetry in the B-H curve, indicated by equation (1), is lost. As a result, the Fourier representation of the B-field as a function of the time will also comprise even-numbered harmonics.

The invention aims at developing a method for detection of and protection against the detrimental effect of static magnetic fields on the performance of magnetoelastic force transducer.

To achieve this aim the invention suggests a method according to the introductory part of claim 1, which is characterized by the features of the characterizing part of claim 1.

Further developments of this method are characterized by the features of the additional claims 2 and 3.

A device for carrying out the method according to the invention is characterized by the features of claim 4.

Further developments of this device are characterized by the features of the additional claims 5 to 9.

Accordingly, the invention comprises a method and a device for determining the presence of even harmonics. Measuring the content of these harmonics gives a measure of the degree of static and/or quasi-static magnetization and the measured value may be used as an input signal to a regulator which, with the aid of a direct current, controls this external magnetization to zero.

In addition, the method according to the invention provides information as to when the achieved protection, in spite of all, is not sufficient and may warn that the transducer does not function satisfactorily, which is very important when the transducer is used in automatic control systems.

If the regulator is not able to fully compensate for the static and/or quasi-static magnetic fields it limits the same, and a warning signal is obtained in a simple manner from the electronics.

A limit as to how rapidly the disturbing quasi-static magnetic field disturbance is allowed to vary is given by the demand that the disturbing magnetization is to change to a small extent during one period of the periodic magnetization.

To manage magnetization in different directions, it is required that the phase position of the second harmonic wave relative to the fundamental wave is kept track of. This is most readily managed by phase-sensitive rectification at the frequency of the second harmonic. This will be described later in more detail.

By way of example, the invention will now be described in greater detail with reference to the accompanying drawings showing in

Figure 1
a symmetrical magnetic hysteresis curve as well as a distorted curve when the material is magnetized by a static magnetic field,

Figure 2
a block diagram of electric equipment according to the invention which manages to detect the external magnetization and control this to zero with the aid of a compensation winding,

Figure 3
a modified block diagram of electric equipment which manages to detect the external magnetization and control this to zero without the help of a compensation winding,

Figures 4, 5 and 6
three different embodiments of the oscillator section in the block diagrams according to Figures 2 and 3,

Figure 7
an embodiment of the phase-sensitive detection of even harmonics in the block diagrams according to Figures 2 and 3,

Figure 8
the principle of applying a compensating winding for preventing static and/or quasi-static magnetic fields from disturbing a magnetoelastic force transducer,
Figure 9
the principle of applying a compensation winding for preventing static and/or quasi-static magnetic fields from disturbing a magnetoelastic torque transducer,
Figure 10
how the compensation may be solved without extra windings according to Figure 3, in the case when the direction of the expected disturbance of the magnetic field coincides with the direction of the magnetizing periodic field.

The effects of the magnetic hysteresis and of a static magnetic field on the relationship between the magnetic field strength H and the magnetic flux density B may be studied with reference to Figure 1. Curve "a" illustrates the symmetrical B-H curve which is completed during one period of the fundamental wave. Curve "b" shows the distortion of curve "a" as a result of the material being magnetized by a static magnetic field. A sinusoidal magnetic field strength H gives according to curve "a" a harmonic content in the magnetic flux density B of 16% of the third harmonic and 6% of the fifth harmonic. A sinusoidal magnetic field strength along with a static magnetization produce a second harmonic in the magnetic flux density B of 18% (curve "b").

A preferred embodiment of the method according to the invention is shown in Figure 2 in the form of a block diagram for electric equipment which prevents disturbing static and/or quasi-static magnetic fields from influencing the measurement of force or torque with a magnetoelastic transducer.

The equipment comprises a voltage source 1 which from its outputs 2 and 3 delivers signals which are locked in relation to each other and which have an exact mutual frequency ratio which is equal to two. The signal from output 2, which has the lower frequency, shall be symmetrical around zero and completely free from even harmonics. It is suitably given a pure sine shape, although a pulsewidth-modulated square wave is also, in principle, possible. The signal from the output 3 with twice the frequency as the signal from output 2 is also to be symmetrical in such a way that the duration of the half-periods is exactly the same.

The signal from output 2 is connected to a first amplifier 4 which feeds the excitation winding 5 of the transducer. The amplifier may be connected so that the supply voltage is current-controlled according to the signal from output 2, or it may be voltage-controlled according to the same signal.

The above two possibilities of supplying current permit tow different methods for detection of even harmonics.

If the exciting current is current-controlled, any even harmonics may be detected in a voltage proportional to the time rate of change of the flux, for example as the induced voltage in a winding 9 parallel to the excitation winding 5. This voltage is supplied to a detector which, for detection of even harmonics, is also supplied with the signal from the output 3 of the voltage source, i.e. the signal with double the frequency of the supply frequency.

If the magnetization supply to the transducer is voltage-controlled, any even harmonics may be detected in a signal proportional to the supply current, for example in the form of the voltage across a shunt in the supply circuit. This signal is supplied to a detector which, for the detection of even harmonics, is also supplied with the signal from the output 3 of the voltage source, i.e. the signal with double the frequency of the supply frequency.

The above methods entail that the content of even harmonics will always be superimposed on the fundamental wave. To obtain a better resolution of the phase-sensitive detector, Figure 2 shows a preferred embodiment which means that both the voltage proportional to the time rate of change of the flux and the voltage proportional to the exciting current are supplied to the detector. The first one of these signals is supplied to input 6 and the second signal is supplied to input 7 of the phase-sensitive detector 8 for detection of even harmonics. The signal 6 is obtained as the induced voltage in a winding 9 parallel to the excitation winding.

A more detailed description of the phase-sensitive detector will be given with reference to Figure 7.

Now, if the transducer is magnetized by a static and/or quasi-static magnetic field, the B-H curve will be distorted as shown in Figure 1 in such a way that even harmonics arise. These harmonics have a definite phase position in relation to the magnetization period. Since the detection takes place in a phase-sensitive manner, various directions of the static magnetization may be distinguished. The signal from output 10 of the detector may therefore be supplied to a regulator 11 which, with or without a separate compensating winding, generates an oppositely directed static magnetic field and reduces the harmonic content of even harmonics to zero.

In the embodiment described in Figure 2, the signal from the output 12 of the regulator has been connected to a second amplifier 13 which, in turn, drives a current through a compensation winding 14 which generates the required oppositely directed field.

In order to obtain a warning signal from the electronics if, despite the compensating signal from the regulator and the second amplifier, the supply is still disturbed by superimposed static and/or quasi-static magnetization, the signal from the output 10 of the detector is connected to a level discriminator 15, whose signal from the output 16 constitutes the required warning.

Figure 3 shows an alternative embodiment of the electric compensation equipment. The signal from the output 12 of the regulator is added in the first amplifier to the signal from the output 2 of the voltage source. In this way, the periodic magnetization will contain a static and/or quasi-static component which compensates for the external disturbance.

If the cable resistance is low, the signal to the input 6 of the detector, instead of being taken from the compensating winding 9, may be taken directly from the supply voltage of the transducer.

If the transducer is supplied with sinusoidal supply voltage and the output signal from the transducer does not change signs when being subjected to load within the measuring range, it is also, in principle, possible to use the output signal of the transducer as a signal to input 6 of the detector.

For certain transducer types, two or more measuring zones with a measuring winding in each zone are used. These are normally connected in opposition to obtain a difference signal. By making the terminals of all measuring windings available, also the total flux in the transducer may be measured and such a sum signal is then also possible to use as input signal 6 to the phase-sensitive detector.

The regulator 11 is suitably designed as an ordinary PI regulator.

Figure 4 shows a method of realizing the voltage source 1 in Figures 2 and 3. The starting-point is a digital frequency generator 17. The output 18 is used directly as the required control signal from the output 3 of the voltage source, and it is also connected to the input of a frequency divider 19. The signal from the output 20 of the frequency divider 19 is thus a square wave with the frequency of half the frequency of the input signal. Finally, the square wave is filtered in a low-pass filter 21 and is then connected to the output 2 of the voltage source.

Figure 5 shows another principle for realizing the voltage source with the aid of a sine generator 22. The output of this generator is connected directly to the output 2 of the voltage source and is also full-wave rectified in a rectifier 23. This creates a signal which contains a frequency component with double the frequency of the sine generator. The rectified signal is then filtered with the band-pass filter 24 and then connected to the output 3 of the voltage source.

Figure 6 shows a third alternative in which two sine generators 25 and 26 are used, which are synchronized via a connection 27.

Figure 7 shows an implementation of the phase-sensitive detector 8 of even harmonics, shown in Figures 2 and 3. The signal arriving at connection 6 is phase-shifted in a phase-shift circuit 28 and passed from the output 29 to a subtractor 30 where it is subtracted from the signal arriving at connection 7 and being proportional to the supply current. The signal level and phase position of the output 29 of the phase-shift circuit are to be adapted such that the signal on the output 31 of the subtractor contains as small a portion as possible with the same frequency as the magnetization of the transducer. The signal on the output of the subtractor is connected to the input of a phase-sensitive rectifier 32. The control signal to the phase-sensitive rectifier is obtained by phase-shifting the signal from the output 3 of the voltage source in a phase-shift circuit 33. The phase-shift is chosen such that the phase of the control signal corresponds to the phase of the second harmonic which arises in the signal on the output from the subtractor when the transducer is subjected to a static magnetic field. The signal on the output 34 from the phase-sensitive rectifier is finally low-pass filtered in a low-pass filter 35.

As previously described, it should be noted that it is not necessary for the function of the detector to subtract the fundamental wave from the voltage signal connected to input 6 and from the current signal connected to input 7, respectively. However, this method reduces the demands for ideality of the phase-sensitive rectifier 32.

Other solutions for implementing the demodulator are, of course, also possible.

In the solutions described above, the various functions have been realized as building blocks designed on the basis of analogue technique. However, there is, of course, nothing preventing realizing the same functions with the use of a digital signal processor.

Figure 8 shows a force transducer 8 which is protected from a static and/or quasi-static magnetic field with the aid of a compensation winding 14 (see Figure 2). The force on the force transducer is applied by way of an end piece 37 which is also capable of conducting static magnetic fields into the transducer. To prevent this, the compensation winding is wound around the end piece. In addition, the transducer is suitably screened off with the aid of a shielding box 38 of highly permeable magnetic material. This protects the transducer from external magnetic fields which are directed across the direction of force. The screen also functions as flux closure yoke for the magnetic field generated by

the compensation winding, which, in turn, reduces the current consumption of the second amplifier 13 according to Figure 2.

Figure 9 shows how a torque transducer 39, with the aid of compensation winding 14, may be protected from a static and/or quasi-static magnetic field which is introduced via a torque-loaded shaft 40. It is shown here that the compensation winding may be wound around the transducer itself instead of around the shaft. Also in this case, an external magnetic screen 41 may be used.

Figure 10 shows an example of how to proceed with a torque transducer for compensation in accordance with the embodiment illustrated in Figure 3. Figure 10 shows, in cross section, the principle of a contactless torque transducer according to, for example, US-A 4,506,554. In this transducer two measuring zones 42 and 43 are magnetized by a time-dependent periodic magnetic field which is generated by two excitation coils 44 and 45 which are series-connected and concentrically arranged around the shaft. The flux is closed by a yoke 46 of highly permeable material. Since the magnetization coincides with the direction of the shaft, the compensating magnetic field may be generated by superimposing a direct current on the periodic exciting current, as indicated in Figure 3.

Claims

1. Method for detection of and protection against the effect of disturbing static and/or quasi-static magnetic fields on measurement with a magnetoelastic force and torque transducer which transducer (36, 39) is magnetized by a symmetrical, periodic supply current, the Fourier representation of which only comprises a fundamental wave and odd harmonics of this fundamental wave **characterized** in that when the transducer is supplied with current, a first signal proportional to the flux in the transducer or its time rate of change is connected to a first input (6) of a phase-sensitive detector (8) the output signal of which is proportional to the content of even harmonics in the Fourier representation of said first signal, or that when the magnetization of the transducer is supplied with voltage, a second signal proportional to the supply current which magnetizes the transducer is connected to a second input (7) of the phase-sensitive detector (8), the output signal of which is proportional to the content of even harmonics in the Fourier representation of this second signal, and that when the output of the phase-sensitive detector is different from zero, detection of disturbing static and/or quasi-static magnetic fields is indicated.

2. A method according to claim 1, **characterized** in that the output of the phase-sensitive detector is connected to the input of a regulator (11), the output signal of which is connected via an amplifier (13) to a compensating winding (14) on the transducer for generating a static and/or quasi static magnetization which is directed in the opposite direction of the disturbing quasi-static magnetization.

3. A method according to claim 1, **characterized** in that the output of the phase-sensitive detector is connected to the input of a regulator (11), the output signal of which is connected for cooperation with the exciting current in order thus to generate, via the excitation winding (5) of the transducer, a static and/or quasi-static magnetization which is connected in the opposite direction of the static and/or quasi-static magnetization.

4. A device for detection of and protection against the effect of disturbing static and/or quasi-static magnetic fields on measurement with a magnetoelastic force and torque transducer which device comprises such a transducer (36, 39) which is magnetized by a symmetrical, periodic supply current, the Fourier representation of which only comprises a fundamental wave and odd harmonics of this fundamental wave, **characterized** in that when the transducer is supplied with current, a first signal proportional to the flux in the transducer or its time rate of change is connected to a first input (6) on a phase-sensitive detector (8) the output signal of which is proportional to the content of even harmonics in the Fourier representation of this first signal, or that when the magnetization of the transducer is supplied with voltage, a second signal proportional to the supply current which magnetizes the transducer is connected to a second input (7) of the phase-sensitive detector (8), the output signal of which is proportional to the content of even harmonics in the Fourier representation of said second signal, and that when the output of the phase-sensitive detector is different from zero, the device is adapted to indicate detection of disturbing static and/or quasi-static magnetic fields.

5. A device according to claim 4, **characterized** in that the output of the detector is connected to the input of a regulator (11), the output signal of which is connected via an amplifier (13) to a compensating winding (14) on the transducer for generating a static and/or quasi-static magnetization which is directed in the

opposite direction of the disturbing static and/or quasi-static magnetization.

6. A device according to claim 4 or 5, **characterized** in that the output of the detector is connected to the input of a regulator (11), the output signal of which cooperates with the exciting current in order thus to generate, via the excitation winding (5) of the transducer, a static and/or quasi-static magnetization which is directed in the opposite direction of the disturbing static and/or quasi-static magnetization.

7. A device according to any of claims 4 to 6, **characterized** in that the supply voltage of the transducer is arranged as the first signal proportional to the time rate of change of the flux through the transducer.

8. A device according to any of claims 4 to 7, **characterized** in that the induced voltage in one or more measuring windings is arranged as the signal proportional to the time rate of change of the flux through the transducer.

9. A device according to any of claims 4 to 8, **characterized** in that the induced voltage in an extra secondary winding parallel to the supply voltage is arranged as the signal proportional to the time rate of change of the flux through the transducer.

FIG. 1

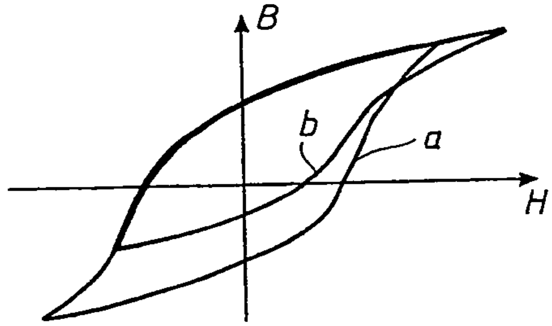


FIG. 2

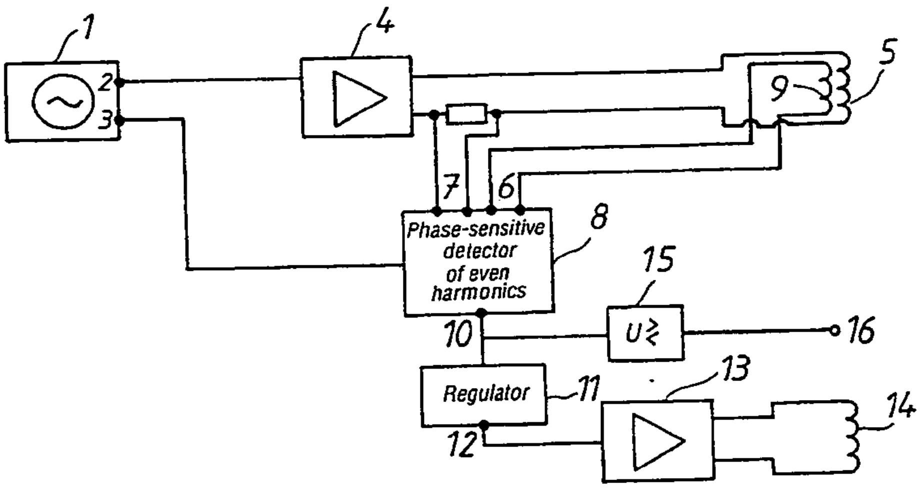


FIG. 3

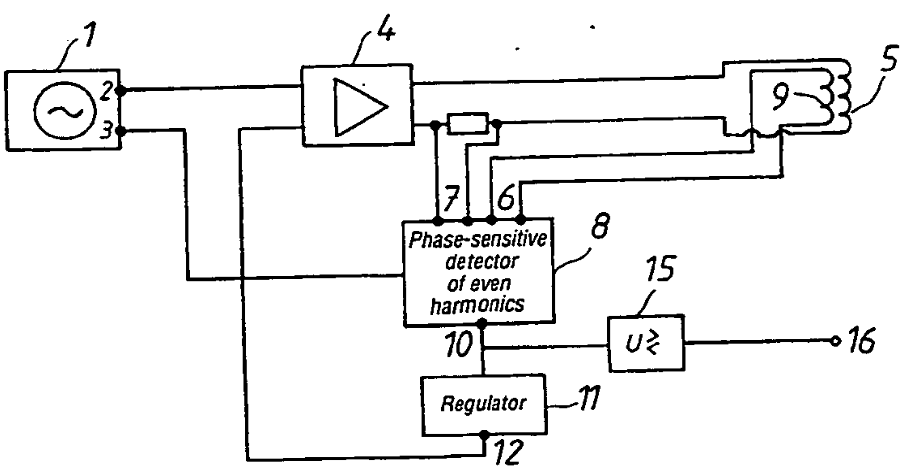


FIG. 4

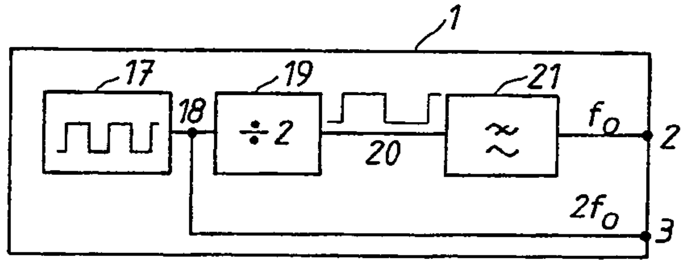


FIG. 5

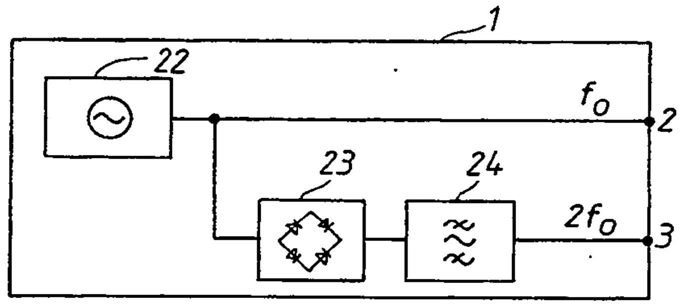


FIG. 6

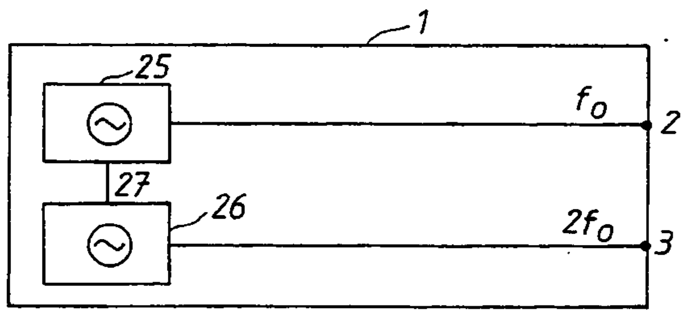


FIG. 7

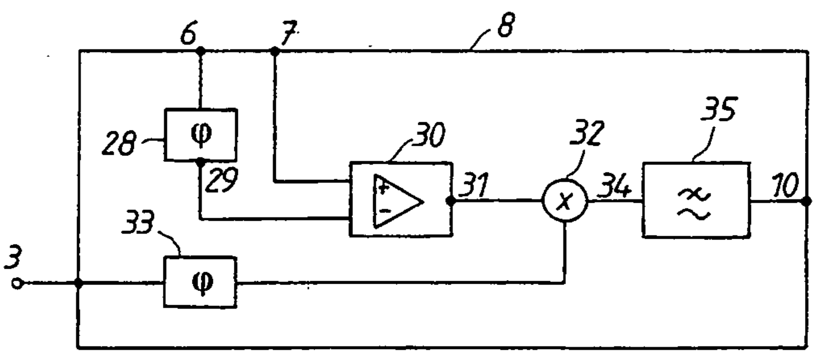


FIG. 8

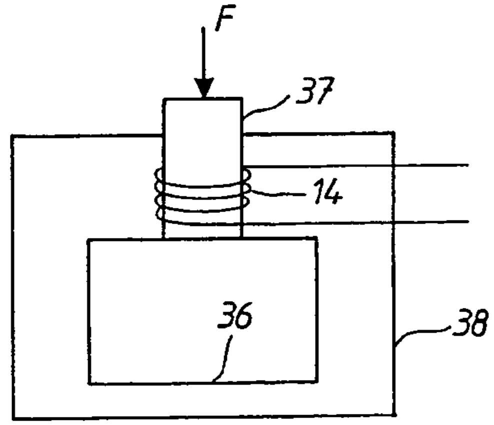


FIG. 9

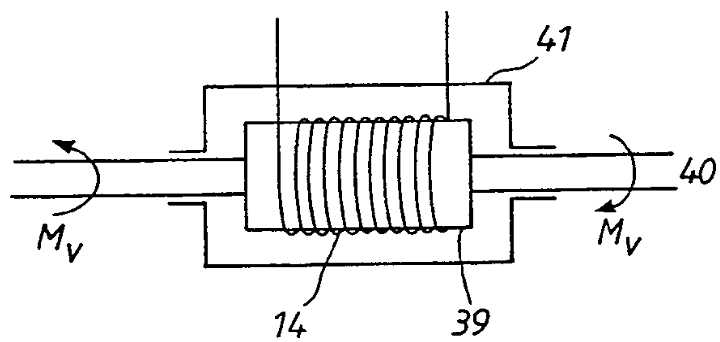
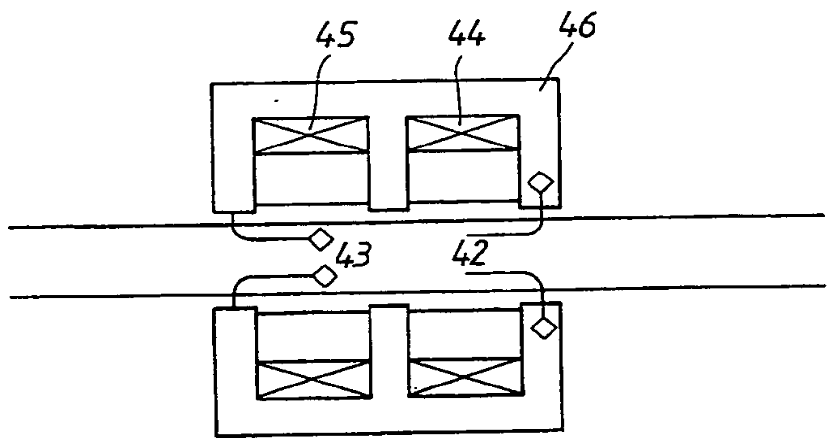


FIG. 10



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EUROPEAN SEARCH REPORT

Application number

90125168.6

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int Cl.5)
A	US-A- 4 716 773 (Y.NANOMURA ET AL) *Abstract, figures 1-7*	1,4	G 01 L 1/12, 3/10

TECHNICAL FIELDS SEARCHED (Int Cl.5)
G 01 B G 01 L

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
STOCKHOLM	14-03-1991	L. JAKOBSSON

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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